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FOR

RELIABLE MULTICARRIER COMMUNICATION IN THE PRESENCE OF PERIODIC IMPULSIVE INTERFERENCE

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RELIABLE MULTICARRIER COMMUNICATION IN THE PRESENCE OF PERIODIC IMPULSIVE INTERFERENCE

TECHNICAL FIELD

[0001]   This disclosure relates generally to communication systems, and more particularly to multicarrier communication in the presence of periodic impulsive interference.

BACKGROUND

[0002]   A Discrete Multi-Tone (DMT) communication system carries information from a transmitter to a receiver over a number of sub-carriers or tones. There are various sources of interference and noise in a DMT system that corrupt the information signal on each tone as it travels through the communication channel and is decoded at the receiver. Because of this signal corruption, the transmitted data may be retrieved erroneously by the receiver. In order to ensure a reliable communication between transmitter and receiver, each tone may carry a limited number of data bits. The number of data bits or the amount of information that a tone carries may vary from tone to tone and depends on the relative power of the information and the corrupting signals on that particular tone.

[0003]   A reliable communication system is typically defined as a system in which the probability of an erroneously detected data bit by the receiver is always less than a target value. The aggregate sources of corruption associated with each tone are commonly modeled as a single noise source with Gaussian distribution that is added to the information signal on that tone. Under these assumptions, the signal-to-noise power

ratio (SNR) becomes a significant factor in determining the maximum number of data bits a tone can carry reliably.

[0004]   The direct relationship between SNR and the bit rate is based on the key assumption of Gaussian distribution for noise. However, this assumption is not completely valid in many practical situations. An important category of such cases is, for example, an environment with periodic impulsive interference from an AC power line. Electric motors and light dimmer switches are examples of such interfering sources. With such noise sources, SNR may not accurately determine the reliable bit rate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005]   Figure 1 illustrates examples of scatter plots and histograms of a normalized

error signal for a particular tone in an ADSL modem when an interfering electric

dimmer is off and on.

[0006]   Figure 2 illustrates an embodiment of a composite noise model consisting of

impulse and Gaussian noise sources.

[0007]   Figure 3 illustrates an embodiment of an equivalent noise model of a

composite noise source.

[0008]   Figures 4A and 4B illustrate examples of time-domain plots for composite

and Gaussian noise sources.

[0009]   Figure 5 illustrates an embodiment of a DMT communication system.

[0010]   Figure 6 illustrates an embodiment of an impulse noise detection method.

[0011]   Figure 7 illustrates an embodiment of a computer system suitable for use in

practicing the present invention.

DETAILED DESCRIPTION

[0012]   In the following detailed description of embodiments of the invention,

reference is made to the accompanying drawings in which like references indicate

similar elements, and in which, by way of illustration, specific embodiments in which

the invention may be practiced are shown. These embodiments are described in

sufficient detail to enable those skilled in the art to practice the invention, and it is to be

understood that other embodiments may be utilized and that logical, mechanical,

electrical, functional and other changes may be made without departing from the scope

of the present invention. The following detailed description is, therefore, not to be taken

in a limiting sense, and the scope of the present invention is defined only by the

appended claims.

[0013]   The interference from impulse noise sources tends to be periodically

impulsive; i.e. strong corrupting power with short duration. Although the maximum

instantaneous power of this type of noise is fairly high, the average power is rather low,

resulting in a large peak-to-average ratio (PAR) – a salient characteristic of these

interfering sources.

[0014]   In an Asymmetric Digital Subscriber Line (ADSL) system, where each tone

is modulated using a Quadrature Amplitude Modulation (QAM) scheme, the error

between the receive and transmit signal is usually depicted in a 2D scatter plot for each

tone. In such a plot, each point corresponds to a data point and represents the amplitude

error of the in-phase and perpendicular components of the carrier. Figure 1 illustrates

examples of such scatter plots 102, 104, along with histograms 106, 108 of the

normalized error signal for a particular tone in a conventional ADSL modem when an

interfering electric dimmer is off and on. The histogram 106 of the error when the

dimmer is off shows a Gaussian distribution for the noise source. When the dimmer is

on, however, the histogram 108 shows side lobes 109a, 109b that correspond to the

outliers 105 on the scatter plot 104.

[0015]   Clearly, a simple Gaussian distribution may not accurately model an impulse

noise source. In one embodiment, a more accurate model is a composite noise model

that includes an impulse noise source as an additive noise besides the original Gaussian

noise source. Figure 2 illustrates an embodiment of a composite noise model 200

consisting of impulse 204 and Gaussian 206 noise sources. The impulse noise 204, in its

simplest form, has a uniformly distributed random phase and a constant amplitude called

impulse amplitude, r. A switch 202 controls the contribution of the impulse noise source

204 to the composite model 200. The switch 202 turns on with a rate called impulse

frequency and remains on for a period called impulse duration. An interfering electric

dimmer, for example, has a fairly constant impulse frequency that is about twice the

frequency of an AC power line. Embodiments of the methods and apparatuses described

herein analyze the bit-error rate with a composite noise source and detect the presence of

an impulse noise source.

[0016]   Equivalent Noise Power

[0017]   A bit-error occurs when the noise amplitude is large enough so that a

received QAM constellation point crosses the so-called decision boundary and is

decoded as a neighboring point. The decision boundaries normally cross midway

between the adjacent constellation points. For a Gaussian noise source, the ratio of the

minimum-distance of constellation points to the power level of noise determines the

bit-error rate. For a fixed power level of noise, the higher the minimum distance is, the lower the probability of error is. When maintaining a target error rate for a given power level of noise, the constellation size may be chosen such that its minimum-distance is above:

$$d_G = \alpha\sigma \tag{1}$$

where d_G denotes the minimum-distance when the noise source is purely Gaussian, σ^2 is the power of the Gaussian noise source, and α is a constant factor that depends significantly on the error rate and the channel coding scheme. For example, in one embodiment, for an uncoded modulation with a target bit-error rate of 10^{-7}, α has a value of about 6.0.

[0018] In one embodiment, to obtain a similar expression for impulse noise, the following three key assumptions may be made:

A.1- The impulse noise has a very small duty cycle; i.e. it only occurs infrequently and for very short periods.

A.2- The impulse noise frequency is much higher than the target error rate.

A.3- The impulse noise amplitude is much larger than the Gaussian noise power.

[0019] The first assumption, A.1, implies that the contribution of impulse noise to the average composite power level of noise is negligible. Therefore, the measured power level of noise is reasonably close to the Gaussian noise power. The last two assumptions, A.2 and A.3, imply that the outliers 105 in the scatter plot 104 of Figure 1 dominate the error events. This is because the outliers are biased off-center and closer to the decision boundaries, and hence are more probable to pass a boundary and result in error. The average distance of outliers from the center of scatter plot equals the impulse

amplitude, resulting in a minimum-distance, which is effectively smaller by twice that value. Therefore, in one embodiment, to maintain a target error rate with an impulsive noise, the minimum-distance is

$$d_I = \alpha\sigma + 2r \qquad (2)$$

where r is the impulse amplitude and d_I denotes the minimum-distance with an impulse noise source.

[0020]   In one embodiment, it is useful to derive an equivalent pure Gaussian noise source that results in the same minimum-distance as a composite noise source. In one embodiment, using equations (1) and (2), the power of the equivalent noise source, σ_e, is derived as:

$$\sigma_e = \sigma\left(1 + \frac{2}{\alpha}\frac{r}{\sigma}\right) \qquad (3).$$

This indicates that for the purpose of bit-error rate analysis and bit-loading, a composite noise source is equivalent to a simple Gaussian noise source with an amplified power. Therefore, in one embodiment, the composite noise model 200 of Figure 2 can be simplified as an equivalent Gaussian noise source illustrated in Figure 3. Figure 3 illustrates an equivalent noise model 300 in which the impulse noise effectively acts as an amplifier for the original Gaussian noise source with an equivalent gain, G_I, where $G_I = 1 + (2/\alpha)(r/\sigma)$. In one embodiment, using assumption A.3, the impulse amplitude r is obtained by measuring the maximum noise value over a finite time interval. Thus, in one embodiment, the ratio r/σ is measured as the peak-to-average (PAR) ratio of the noise, and the equivalent gain (i.e. gain factor) of an impulse noise can be expressed as:

$$G_I = 1 + \left(\frac{2}{\alpha}\right)PAR \qquad (4).$$

[0021]   It should be noted that the assumptions that led to the equivalent noise model 300 and the corresponding effective gain for impulse noise only hold when the PAR is large enough. When the PAR is small, the Gaussian noise is the dominant noise source and a simple Gaussian model is applicable. For example, in one embodiment, the expected value of PAR for a Guassian noise source measured over 1000 samples is about 3.0; with an impulse noise, the measured PAR may be above 4.0.

[0022]   Impulse Noise Detection

[0023]   To apply the equivalent noise model 300 derived above, the presence of impulse noise must be detected. In one embodiment, a salient feature that is used to distinguish a composite noise from a pure Gaussian noise source is the higher rate of outliers 105 in the scatter plot 104, illustrated in Figure 1. These outliers form the large error samples or spikes 402 in the time-domain plot illustrated in Figure 4A. The error amplitude in the plots illustrated in Figures 4A and 4B is normalized to the standard deviation of the noise. An error sample is defined as a spike error if its normalized amplitude is above a preset spike threshold. Figure 4B illustrates that the spike rate with a pure Gaussian noise source is much lower than that with a composite noise source, as illustrated in Figure 4A.

[0024]   The probability of a spike error for a Gaussian noise source can be derived from the so-called Complementary Error Function. This probability is calculated to be exceeding smaller as the spike threshold is set higher. For instance, in one embodiment, spike threshold values of 3, 4 and 5 result in spike rates of 2.7×10^{-3}, 6.3×10^{-5} and 5.7×10^{-7}, respectively. On the other hand, the spike rate with an impulse noise source is much higher and fairly constant over a wide range of threshold values. For example,

in one embodiment, an electric dimmer with AC power frequency of 60 Hz can generate

a spike rate in the order of 3×10^{-2} in an ADSL system where the sampling rate is about

4 KHz. In the example illustrated in Figure 4A, this rate changes only slightly as the

spike threshold varies from 3 to 5.

[0025]   A system level overview of the operation of an embodiment of the invention

is described with reference to Figure 5. Figure 5 illustrates an embodiment of a DMT

communication system 500. A transmitter 502 at a central office transmits a multicarrier

signal 503 (e.g. a DMT signal) to a receiver DSL modem 504. As the signal 503 travels

to the modem 504 through a transmission channel (e.g. a telephone line), the signal is

potentially corrupted by both Gaussian 506 and Impulse 508 noise sources. Once the

signal 503 is received at the modem 504, a Fast Fourier Transform (FFT) block 510

transforms samples of the signal from the time-domain to the frequency-domain, such

that a stream of data for each sub-carrier may be output. In one embodiment, processing

of each sub-carrier may be performed in parallel or in serial.

[0026]   For a particular sub-carrier of the multicarrier signal, a Noise Power

Measurement block 514 measures the power level of noise for the sub-carrier. An

Impulse Noise Detector 512 detects whether an impulse noise source is present in the

sub-carrier signal. If impulse noise is detected in the sub-carrier, detector 512

determines a Gain Factor G_I 518 associated with the impulse noise. The gain factor 518

is multiplied 520 with the power level of noise for the sub-carrier to obtain an equivalent

noise power. The equivalent noise power is input into a Signal-to-Noise Ratio (SNR)

block 522.

[0027]   A Signal Power Measurement block 516 measures the signal power for the

sub-carrier, and inputs the result into the SNR block 522. The SNR block determines a

signal-to-noise ratio, which is used to determine bit loading 524 for the sub-carrier. The

particular methods used in the system 500 are described below with respect to a series of

flow charts.

[0028]   <u>Noise Power Measurement in ADSL</u>

[0029]   In one embodiment, the present invention provides for the automatic

detection of an impulse noise source and calculation of the equivalent noise power in a

DMT communication system. Figure 6 illustrates an embodiment of an impulse noise

detection method 600, which may be implemented in the system 500 illustrated in Figure

5. For example, in one embodiment, the method 600 is implemented in the impulse

noise detector 512 and noise power measurement block 514 of Figure 5.

[0030]   The method 600 illustrated in Figure 6 constitutes a computer program made

up of computer-executable instructions illustrated as blocks (acts) from 600 until 622.

Describing the method by reference to a flow chart enables one skilled in the art to

develop such programs including such instructions to carry out the methods on suitably

configured computers (the processor of the computer executing the instructions from

computer-readable media, including memory). The computer-executable instructions

may be written in a computer programming language or may be embodied in firmware

logic. If written in a programming language conforming to a recognized standard, such

instructions can be executed on a variety of hardware platforms and for interface to a

variety of operating systems. In addition, the present invention is not described with

reference to any particular programming language. It will be appreciated that a variety

of programming languages may be used to implement the teachings of the invention as described herein. Furthermore, it is common in the art to speak of software, in one form or another (e.g., program, procedure, process, application, module, logic...), as taking an action or causing a result. Such expressions are merely a shorthand way of saying that execution of the software by a computer causes the processor of the computer to perform an action or produce a result. It will be appreciated that more or fewer processes may be incorporated into the method illustrated in Figure 6 without departing from the scope of the invention and that no particular order is implied by the arrangement of blocks shown and described herein.

[0031]   In one embodiment, the noise source is detected by the method 600 and labeled as impulsive based on the aggregate data from all sub-carriers. If the noise source is detected as impulsive, then the method 600 calculates the effective impulse gain and equivalent noise source for each sub-carrier independently. In another embodiment, an impulse noise detection method calculates a single impulse gain to be applied to all sub-carriers of the signal. In one embodiment, processing of each sub-carrier may be performed in parallel or in serial.

[0032]   In one embodiment, at block 601, the method 600 measures the power level of noise for each sub-carrier. In one embodiment, error samples, e_i , are measured over a finite time interval of n samples for each sub-carrier. The noise power measurement is updated regularly after a new set of error samples are collected. In one embodiment, the sampling rate is about 4 KHz in an ADSL system. For each sub-carrier, the method 600 calculates the standard deviation or the RMS value of the error samples as:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n} e_i^2$$
(5),

where σ^2 is the power of the Gaussian noise source for a particular sub-carrier.

[0033] At block 602, the method 600 determines the maximum error amplitude for each sub-carrier of the signal. For each sub-carrier, the method 600 calculates the maximum error amplitude, m, as:

$$m = MAX(| e_i |) \qquad (6).$$

[0034] At block 604, for each sub-carrier, the method 600 calculates the spike rate, s, as:

$$s = \frac{1}{n} \text{ number of } (| e_i | > spike\_threshold) \qquad (7).$$

In one embodiment, a spike is an error having a normalized error amplitude above a spike threshold. For example, in one embodiment, the spike threshold is about 4.5.

[0035] At block 606, the method 600 calculates the number of carriers with large spike rates as:

$$large\_rate\_carriers = \text{number of carriers with } (s > rate\_threshold) \qquad (8).$$

In one embodiment, a large spike rate is a spike rate, s, above a rate threshold. For example, in one embodiment, the rate threshold is about 0.3. The rate threshold depends on the specifics of a particular implementation.

[0036] At block 608, the method 600 determines whether the number of carriers with large spike rates is greater than a carrier threshold (i.e. whether $larger\_rate\_carriers > carrier\_threshold$). In one embodiment, the carrier threshold is about 10% of the total number of carriers. If the number of carriers with large spike rates is not greater than a carrier threshold, then no impulse noise is detected by the method 600 at block 610. In one embodiment, if no impulse noise is detected by the method 600 at block 608, the gain factor G_I is set to $G_I=1$ for all sub-carriers, and the

method 600 ends. In another embodiment, where no impulse noise is detected by the method 600 at block 608, no gain factor is determined, and the original noise power measurement for all sub-carriers is not modified.

[0037] In one embodiment, if the number of carriers with large spike rates is determined by the method 600 at block 608 to be greater than the carrier threshold, the method 600 performs the acts represented by blocks 612 to 622 for each sub-carrier of the signal. In one embodiment, processing of each sub-carrier may be performed in parallel or in serial. At block 614, the method 600 measures the peak-to-average ratio for each sub-carrier as:

$$PAR = \frac{m}{\sigma} \tag{9},$$

where m is the maximum error amplitude and σ^2 is the power of the Gaussian noise source for a particular sub-carrier.

[0038] For each sub-carrier, the method 600 determines at block 616 whether the PAR for the particular sub-carrier is greater than a PAR threshold (i.e. whether $PAR >$ $PAR\_threshold$). In one embodiment, the PAR threshold is about 4.5. In another embodiment, each sub-carrier has a specific PAR threshold. If the method 600 determines at block 616 that the PAR for the particular sub-carrier is not greater than a PAR threshold, the gain factor G_l is set to $G_l = 1$ at block 618. If the method 600 determines at block 616 that the PAR for the particular sub-carrier is greater than a PAR threshold, then the method 600 determines a gain factor G_l for the particular sub-carrier at block 617. In one embodiment, the gain factor G_l is determined as described above with respect to Equation (4).

[0039]   At block 620, the method 600 calculates the equivalent noise power for the particular sub-carrier by multiplying the gain factor G_l by the power of the Gaussian noise source measured by the method 600 at block 601. In one embodiment, the power of the equivalent noise source σ_e for the particular sub-carrier is calculated as:

$$\sigma_e = \sigma \left(1 + \frac{2}{\alpha} PAR \right) \qquad (10).$$

[0040]   The final value of equivalent noise power, $\sigma_e{}^2$, can be used in any bit-loading algorithm that is designed specifically for Gaussian noise sources. For example, in one embodiment, the equivalent noise power calculated by the method 600 is used to determine the SNR for the sub-carrier. Subsequently, the SNR based on the equivalent noise power is used to determine a bit-loading for the sub-carrier in the presence of impulse noise. The resulting bit-error rate remains at target value even if the noise source is not purely Gaussian and consists of an impulsive component.

[0041]   In one embodiment, the method 600 is implemented more robustly by introducing hysterisis when a comparison with a threshold is made. This minimizes the frequent switching of the gain factor on and off once impulse noise is detected for a certain tone. In one embodiment, this aspect is implemented by using a different threshold once impulse noise is detected for a particular sub-carrier. In one embodiment, this is accomplished using variations of the spike threshold or the rate threshold. For example, in one embodiment, initially a higher spike threshold may be used to initially detect an impulse noise source. However, once an impulse noise source is detected, a lower spike threshold is used to detect the impulse noise source. This may be similarly

implemented with the rate threshold. The result is a better user experience, since fluctuation between impulse noise compensation and non-compensation is minimized.

[0042]   Although embodiments of the present invention are described primarily with respect to the detection and compensation for impulsive noise sources, it will be appreciated that embodiments of the present invention may be applied to compensate for other types of non-Gaussian noise sources. For example, phase noise, a type of non-Gaussian noise, may be compensated for by determining a gain factor associated with the phase noise, and applying the gain factor to determine an equivalent noise power.

[0043]   Furthermore, although embodiments of the present invention are described primarily with respect to ADSL systems using DMT modulation, it will be appreciated that embodiments of the present invention are not limited thereto. For example, embodiments of the present invention are applicable to other versions of DSL, such as, but not limited to, Rate Adaptive DSL (RADSL), Very High Bit Rate DSL (VDSL or VHDSL), High Bit Rate DSL (HDSL), Symmetric DSL (SDSL), and ISDN DSL (IDSL), as well as communications systems using other modulation techniques. Embodiments of the present invention are applicable to communication systems employing carrier signals in general. For example, in a single carrier system, impulse noise may be detected and compensated for by modeling the impulsive noise as described above, and generating a gain factor associated with the impulsive noise source.

[0044]   Figure 7 is one embodiment of a computer system that may be used with embodiments of the present invention. It will be apparent to those of ordinary skill in the art, however that other alternative systems of various system architectures may also be used.

[0045]   The data processing system illustrated in Figure 7 includes a bus or other

internal communication means 715 for communicating information, and a processor 710

coupled to the bus 715 for processing information. The system further comprises a

random access memory (RAM) or other volatile storage device 750 (referred to as

memory), coupled to bus 715 for storing information and instructions to be executed by

processor 710. Main memory 750 also may be used for storing temporary variables or

other intermediate information during execution of instructions by processor 710. The

system also comprises a read only memory (ROM) and/or static storage device 720

coupled to bus 715 for storing static information and instructions for processor 710, and

a data storage device 725 such as a magnetic disk or optical disk and its corresponding

disk drive. Data storage device 725 is coupled to bus 715 for storing information and

instructions.

[0046]   The system may further be coupled to a display device 770, such as a cathode

ray tube (CRT) or a liquid crystal display (LCD) coupled to bus 715 through bus 765 for

displaying information to a computer user. An alphanumeric input device 775, including

alphanumeric and other keys, may also be coupled to bus 715 through bus 765 for

communicating information and command selections to processor 710. An additional

user input device is cursor control device 780, such as a mouse, a trackball, stylus, or

cursor direction keys coupled to bus 715 through bus 765 for communicating direction

information and command selections to processor 710, and for controlling cursor

movement on display device 770.

[0047]   Another device, which may optionally be coupled to computer system 700, is

a communication device 790 for accessing other nodes of a distributed system via a

network. The communication device 790 may include any of a number of commercially available networking peripheral devices such as those used for coupling to an Ethernet, token ring, Internet, or wide area network. The communication device 790 may further be a null-modem connection, a wireless connection mechanism, or any other mechanism that provides connectivity between the computer system 700 and the outside world. Note that any or all of the components of this system illustrated in Figure 7 and associated hardware may be used in various embodiments of the present invention.

[0048]   It will be appreciated by those of ordinary skill in the art that any configuration of the system may be used for various purposes according to the particular implementation. The control logic or software implementing the present invention can be stored in main memory 750, mass storage device 725, or any machine-readable medium locally or remotely accessible to processor 710. A machine-readable medium includes any mechanism for storing or transmitting information in a form readable by a machine (e.g. a computer). For example, a machine readable medium includes read-only memory (ROM), random access memory (RAM), magnetic disk storage media, optical storage media, flash memory devices, electrical, optical, acoustical or other forms of propagated signals (e.g. carrier waves, infrared signals, digital signals, etc.).

[0049]   It will be apparent to those of ordinary skill in the art that the system, method, and process described herein can be implemented as software stored in main memory 750 or read only memory 720 and executed by processor 710. This control logic or software may also be resident on an article of manufacture comprising a computer readable medium having computer readable program code embodied therein and being

readable by the mass storage device 725 and for causing the processor 710 to operate in accordance with the methods and teachings herein.

[0050] The present invention may also be embodied in a handheld or portable device containing a subset of the computer hardware components described above. For example, the handheld device may be configured to contain only the bus 715, the processor 710, and memory 750 and/or 725. The present invention may also be embodied in a special purpose appliance including a subset of the computer hardware components described above. For example, the appliance may include a processor 710, a data storage device 725, a bus 715, and memory 750, and only rudimentary communications mechanisms, such as a small touch-screen that permits the user to communicate in a basic manner with the device. In general, the more special-purpose the device is, the fewer of the elements need be present for the device to function. In some devices, communications with the user may be through a touch-based screen, or similar mechanism.

[0051] Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0052] The above description of illustrated embodiments of the invention, including what is described in the Abstract, is not intended to be exhaustive or to limit the

invention to the precise forms or embodiments disclosed. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. These modifications can be made to embodiments of the invention in light of the above detailed description. The terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of the invention is to be determined entirely by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.